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In vitro near-infrared imaging of occlusal dental caries using germanium enhanced CMOS camera

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Abstract

The high transparency of dental enamel in the near-infrared (NIR) at 1310-nm can be exploited for imaging dental caries without the use of ionizing radiation. The objective of this study was to determine whether the lesion contrast derived from NIR transillumination can be used to estimate lesion severity. Another aim was to compare the performance of a new Ge enhanced complementary metal-oxide-semiconductor (CMOS) based NIR imaging camera with the InGaAs focal plane array (FPA). Extracted human teeth (n=52) with natural occlusal caries were imaged with both cameras at 1310-nm and the image contrast between sound and carious regions was calculated. After NIR imaging, teeth were sectioned and examined using more established methods, namely polarized light microscopy (PLM) and transverse microradiography (TMR) to calculate lesion severity. Lesions were then classified into 4 categories according to the lesion severity. Lesion contrast increased significantly with lesion severity for both cameras ($p<0.05$). The Ge enhanced CMOS camera equipped with the larger array and smaller pixels yielded higher contrast values compared with the smaller InGaAs FPA ($p<0.01$). Results demonstrate that NIR lesion contrast can be used to estimate lesion severity.

Keywords

Near-IR imaging; occlusal surfaces; dental caries; transillumination

1. INTRODUCTION

Optical transillumination was used extensively before the discovery of x-rays for detection of dental caries. Over the past two decades there has been continued interest in this method, especially with the availability of high intensity fiber optic based illumination systems for the detection of interproximal lesions (1–6). During fiber optic transillumination (FOTI) a carious lesion appears dark upon transillumination because of decreased transmission due to increased scattering and absorption by the lesion. A digital fiber optic transillumination system, called DiFoti, that utilizes visible light for the detection of caries lesions, has been developed by Electro-optics Sciences, Irvington, NY (7). Several studies have been carried out using visible light transillumination either as an adjunct to bitewing radiography or as a competing method for the detection of interproximal caries lesions (8–12). However, since

this system operates in the visible range where light scattering by the sound enamel is significant the results are mixed.

Near-IR light can penetrate much further through tooth enamel due to the markedly longer mean free path of the photons, i.e., enamel is virtually transparent in the near-IR with optical attenuation 1–2 orders of magnitude less than in the visible range(13, 14). Transillumination imaging at longer wavelengths in the near-IR has been investigated in the region accessible to conventional silicon based CCD cameras, namely 830-nm(15, 16) and at 1310–1550 nm (17) where maximal transmission occurs. Near-IR images were acquired of simulated and natural caries lesions on extracted human teeth. Two setups were employed in these near-IR studies one optimized for imaging interproximal lesions through transillumination of teeth(16) and another system that enabled the acquisition of fairly uniform high contrast images of occlusal lesions(17). Various light sources were investigated for NIR imaging including Fabry-Perot NIR diode lasers, tungsten-halogen lamps and broadband superluminescent diodes (SLD). The SLDs provided a high intensity uniform illumination source from an optical fiber and the high bandwidth avoided the production of laser speckle for better images. Even though the light scattering for sound enamel is at a minimum in the NIR, the light scattering coefficient of enamel increases by 2–3 order of magnitude upon demineralization due to the formation of pores—on a similar size scale to the wavelength of the light—that act as Mie scatterers (18). Transmission measurements through demineralized tissue sections at 1310-nm show that demineralized enamel attenuates the laser beam by a factor of 20–50 times greater than sound enamel(19, 20).

Early enamel white spot lesions can be discriminated from sound enamel by visual observation or by visible-light diffuse reflectance imaging (21, 22). The visibility of scattering structures on highly reflective surfaces such as teeth can be enhanced by use of crossed polarizers to remove the glare from the surface due to the strong specular reflection from the enamel surface (23, 24). The contrast between sound and demineralized enamel can be further enhanced by depolarization of the scattered light in the area of demineralized enamel (25, 26). The contrast between sound and demineralized enamel is greatest in the near-IR due to the minimal scattering of sound enamel and this can be exploited for reflectance imaging of early demineralization (18). Wu et al.(27) reported the first high contrast polarized reflectance images of early demineralization on buccal and occlusal tooth surfaces measured at $\lambda=1310$ -nm and found that the contrast was significantly higher at 1310-nm than in the visible range.

Two distinct advantages were noted in our previous NIR imaging studies over visible light methods. In NIR images of the occlusal surfaces, stains were often not visible since the organic molecules responsible for pigmentation absorb poorly in the near-IR(17) making it easier to identify areas of demineralization. Mild developmental defects(28) and shallow demineralization(27) appeared differently from deeper more severe demineralization due to caries suggesting that we may be able to gauge the severity of lesions by analyzing both NIR reflective images and NIR transillumination images of these surfaces.

Our previous near-IR imaging studies utilized InGaAs focal plane arrays (FPA) that were of low pixel density (25- μ m pixel) and an array size of 320 by 240 pixels. InGaAs FPA's are

very expensive and challenging to manufacture. A new near-IR imaging technology, Ge enhanced CMOS (complementary metal-oxide semiconductor) can potentially be less expensive and more practical for low cost, high volume manufacturing. Moreover the camera provided by Noble Peak Vision (Wakefield, MA) had a larger array size (640×240) and higher pixel density (10- μm pixel). The purpose of this imaging study was to compare the image contrast of natural caries lesions measured using these two near-IR imaging technologies.

2. MATERIALS AND METHODS

2.1 Sample preparation

Extracted teeth ($n=52$) from patients in the San Francisco bay area were collected with approval from the UCSF Committee on Human Research, cleaned, sterilized with gamma radiation, and stored in a 0.1% thymol solution to preserve tissue hydration and to prevent bacterial growth. Radiographs and visible light images were acquired of each tooth.

2.2 Near infrared (NIR) imaging

Two different types of devices were used to capture NIR transillumination images. The first device used was a high sensitivity InGaAs FPA, Model SU320KTSX from Sensors Unlimited (Princeton, NJ). The second device used was a Ge enhanced CMOS image sensor, Model NP-EC700M-01 evaluation camera from NoblePeak Vision (Wakefield, MA). NIR light was provided by a $\lambda=1310\text{nm}$ superluminescent diode (SLD) with an output power of 15mW and a 35nm bandwidth, Model SLED1300D20A from Optospeed (Zurich, Switzerland). NIR transillumination images were taken using the configurations shown in Fig. 1. The InGaAs FPA setup utilized the novel arrangement that we previously used for *in vivo* imaging, incorporating two fibers with Teflon optical diffusers aimed at a position just above the cementum-enamel junction (CEJ) of each tooth (Fig. 1A). For the Ge CMOS camera, the output from the optical fiber was collimated by a 20-mm in diameter NIR fiber-collimator from μLS Micro Laser Systems (Garden Grove, CA) and focused by a 150mm focal length cylindrical lens at a position just above the CEJ of each tooth (Fig. 1B). A sheet of light aimed at the cementum-enamel junction moves coronally through the tooth and finally reaches the camera. This is the same setup that we used in previous *in vitro* occlusal imaging studies(17).

2.3 Polarized light microscopy

The teeth were mounted on orthodontic resin blocks that are used for both imaging and for histological sectioning. Sections 200- μm thick were cut using a linear precision saw, the IsoMet 5000 (Buehler, Lake Buff, IL). Polarized light microscopy (PLM) was carried out using a Meiji Techno RZT microscope (Saitama, Japan) with an integrated digital camera, Canon EOS Digital Rebel XT from Canon Inc. (Tokyo, Japan). The sample sections were imbibed in water and examined in the brightfield mode with cross polarizers and a red I plate with 500-nm retardation.

2.4. Transverse microradiography

Thin sections used in PLM were also imaged using transverse microradiography (TMR). A custom-built digital TMR system was used to measure mineral loss in the different partitions of the sample(29). A high-speed motion control system with Newport (Irvine, CA) UTM150 and 850G stages and an ESP300 controller coupled to a video microscopy and laser targeting system was used for precise positioning of the tooth samples in the field of view of the imaging system. The volume percent mineral for each sample thin section was determined by comparison with a calibration curve of X-ray intensity vs. sample thickness created using sound enamel sections of 86.3 ± 1.9 vol.% mineral varying from 50 to 300 μm in thickness. The calibration curve was validated via comparison with cross-sectional microhardness measurements. The volume percent mineral determined using microradiography for section thickness ranging from 50 to 300- μm highly correlated with the volume percent mineral determined using microhardness $r^2 = 0.99$ (29).

2.5 Histology and Image analysis

Lesions were examined and classified according to the lesion depth as follows: (E1) less than half way to the dentinal-enamel junction (DEJ), (E2) more than half way to the DEJ, (D1) penetration to the DEJ but less than half way to the pulp chamber, and (D2), more than half way through the dentin into the inner dentin adjacent to the pulp chamber.

Line profiles were extracted from each image aligned with the histological sections and lesion or image contrast was calculated using $(I_S - I_L)/I_S$; where I_S is the mean intensity of the sound enamel, and I_L is the mean intensity of the lesion area. The image contrast varies from 0 to 1 with 1 being very high contrast and 0 being no contrast. All image analysis was carried out using Igor Pro software from Wavemetrics (Lake Oswego, OR). A one way analysis of variance (ANOVA) followed by the Tukey-Kramer post hoc multiple comparison test was used to compare groups for each type of lesion employing InStat software from GraphPad (San Diego, CA)

3. RESULTS

Figure 2 shows several images of a 3rd molar tooth taken using visible light reflectance and NIR transillumination using both NIR imaging technologies along with a bitewing radiograph and PLM images of two sections that were cut along the yellow dotted lines as indicated in Fig. 2A. The reflectance visible image manifests staining and discoloration however there is no decay visible in the radiograph. Therefore the conventional methods of examination do not reveal the severity of the occlusal decay. The histological sections of Fig. 2C&D indicate that the lesion does not penetrate into dentin. The NIR transillumination images shown in Fig 2E & F show the lesion areas with high contrast without the interference of staining and discoloration and these areas of high contrast match the positions of deep lesion penetration indicated in the histology. Staining and discoloration can interfere with reflectance imaging in the visible region, however the chromophores responsible for stains do not absorb NIR light and therefore do not interfere at NIR wavelengths as can be seen by comparing the NIR images of Figs. 2E & F with Fig. 2A. Polarized microscopy images of the two cross sections are also shown in Figs. 2C & D. Opaque regions in PLM images of

enamel indicate areas of demineralization and they are easy to distinguish from the transparent sound regions. However, it is more difficult to differentiate dentin lesions from sound dentin using PLM alone. For the samples that were difficult to classify by using PLM, TMR was used to verify severity of the lesion.

Table I lists the lesion severity for the 52 lesions included in this study along with the lesion contrast measured for the two imaging technologies and imaging setups. The lesion contrast increased with the lesion severity that was determined using PLM and TMR analysis of the histological thin sections. The image contrast for the enamel only lesions E (E1&E2) was significantly lower than the lesions that penetrated to dentin with the Ge-CMOS setup ($P<0.05$) and the lesion contrast values of the groups E, D1 and D2 were significantly different from one another. For the InGaAs FPA, E1 broke with D1 and D2 but E2 did not break statistically with either E1 and D1. The lesion contrast is displayed graphically in Fig. 3 for both imaging systems.

4. DISCUSSION

Our goal is to achieve the optimum lesion contrast for improved discrimination of demineralization in the important occlusal surfaces where most new decay is found and determine whether the lesion contrast derived from NIR transillumination can be used as an estimate lesion depth or severity. Two near-IR imaging technologies were compared in this study; a new potentially lower cost Ge enhanced CMOS based NIR imaging camera with a larger array size and higher pixel density and a compact InGaAs FPA. The Ge CMOS was also a prototype that was too large to be feasible for clinical use while the InGaAs FPA system could be used for *in vivo* imaging.

It appears that the higher pixel density and larger array size of the Ge enhanced CMOS camera provided increased contrast of the occlusal lesions and this increase in contrast was sufficient to demonstrate a significant difference in the mean contrast between the lesions confined to enamel and the deeper dentin lesions. This is particularly important because the clinician needs to make a treatment decision whether surgical intervention is necessary or more conservative chemical intervention will suffice. Penetration of the lesion deep into dentin is one key indicator for surgical intervention. The D2 lesions are the most likely lesions to require surgical intervention, i.e., least likely to be arrested by chemical intervention or fluoride treatment and the contrast of those lesions was significantly higher for both imaging systems.

Our previous study(30) utilized a cylindrical lens for illumination with the InGaAs FPA camera, i.e., the same setup employed in this study with the Ge-CMOS camera (Fig. 1B). In that study, the lesion contrast of the enamel lesions, E1 and E2 groups combined, did not statistically break with that of D1 group. However in this study, both cameras showed a significant difference between the enamel lesions and the outer dentin lesions ($p<0.05$). This significant improvement using the InGaAs FPA may be due to the novel illumination setup using two NIR light sources (Fig. 1A).

This study clearly demonstrates that the Ge enhanced CMOS camera has considerable potential for the imaging occlusal caries with high contrast. Future goals include utilizing

this new Ge enhanced CMOS NIR transillumination imaging technology with multiple light sources for even distribution of light diffusion around the tooth and in detection of occlusal caries *in-vivo*.

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Fig. 1.

NIR transillumination through the occlusal surface (A) InGaAs SWIR camera setup, and (B) Ge enhanced CMOS camera setup.

Fig. 2.

(A) Visible-light reflectance image, (B) radiograph, (C, D) PLM images of the sections cut along the yellow dotted lines in Fig. 2A. NIR transillumination images captured with the (E) Ge enhanced CMOS camera and (F) NIR InGaAs FPA.

Fig. 3.
Lesion contrast for the Ge enhanced CMOS and InGaAs FPA imaging systems.

Table I

Mean contrast ratio for Ge-CMOS and InGaAs FPA imaging systems

Lesion Category	N	Lesion Contrast Ge (CMOS)	Lesion Contrast (InGaAs FPA)
E1	7	0.30±0.065 a	0.26±0.090 a
E2	15	0.35±0.086 a	0.34±0.091 a, b
D1	13	0.45±0.059 b	0.39±0.071 b
D2	17	0.53±0.086 c	0.47±0.068 c

* Groups sharing alphabet letters are statistically similar $p>0.05$.